Experimental Evaluation of Nonlinear Wave/Damage Interaction for Delamination Detection in Laminated Composites

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Abstract. Structural health monitoring (SHM) deals with the early detection of structural damages to prevent catastrophic failures and is expected to provide major improvements with respect to safety and maintenance costs. With the increasing development of aeronautic industry, composite materials are being more and more widely used. In this case, the SHM of composite structure is crucial, especially the monitoring of local delamination of plies in composite materials. This paper presents an investigation on the detection of delamination type damage in carbon fiber reinforced polymer (CFRP) composite plates based on nonlinear acoustic effects. The LASER shock wave technique is used to generate realistic delamination in the composite plates. A damage index (DI) is proposed in this paper based on total harmonic distortion (THD) to evaluate the nonlinear acoustic effects induced by delamination. Experiments are conducted on four plates containing different sizes of delamination, including one undamaged plate for reference. Results show that acoustic nonlinearities are generated due to the presence of a realistic delamination damage, and the proposed DI is appropriate to evaluate the influence of the delamination size on the nonlinear acoustic effects under different excitation amplitudes.

Keywords: Structural healthy monitoring (SHM) · Delamination · Nonlinear lamb wave · Damage index

1 Introduction

One of the most important issues in engineering is the monitoring and the early detection of structural damages to prevent catastrophic failures. This process is referred to as Structural Health Monitoring (SHM) and its implementation is expected to provide considerable improvements with respect to safety and maintenance costs [1].

In order to test and validate delamination detection algorithms for SHM, experimental investigations are mandatory, and particularly physical supports are firstly needed. In this paper, a new method named Laser Shock Wave Technique (LSWT) [2] is used to generate calibrated delamination damages in composites samples. With this method, only delamination-type damage is generated inside the specimen and its through-thickness location and size of the damage can be well controlled. Furthermore,

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this technique generates a realistic delamination damage compared to traditional damage generation technique, such as Teflon insert.

Various SHM algorithms for damage detection in a SHM context have been investigated. Among them the wave propagation-based method has become the most commonly used method for its convenience and low cost. Specifically, Lamb waves are widely used in beam- and plate-like structures [3–5]. Compared to linear techniques, nonlinear Lamb waves are more sensitive to smaller, even barely visible damages, for example, delamination in composite structures [6].

Generally, the nonlinear phenomena are induced due to various types of physical mechanisms. In this paper, the mechanism named contact acoustic nonlinearity (CAN) [7] is focused. When the incident wave passes through the damage, the damage interfaces tend to move towards each other under compressive pressure, and opposite each other under tensile pressure [7]. This may lead to the contact between damage interfaces, and then higher harmonics can be generated due to this contact interaction [8–10]. Several studies focused on the higher harmonics generated by CAN in composite plates or beams containing delamination damage. Soleimanpour *et al.* [9] studied the potential of a baseline-free SHM techniques based on higher harmonics resulting from the interaction of guided wave with a delamination. Sohn *et al.* [11] explored the feasibility of using a non-contact guided wave imaging system to detect hidden delamination in multi-layer composites.

Despite these studies, there is still no study performing the SHM algorithm for the detection of a realistic delamination-type damage in composite plates. It can be observed that all the above-mentioned experimental studies were performed on structures containing artificial delaminations or cracks, which might cause errors in applications when realistic delamination is present. In this study, composite plates containing realistic delaminations fabricated by laser shock were investigated. These calibrated delaminations are able to imitate physically the real delamination existed in a composite structure.

The objective of this study is thus to investigate the physical mechanism of the generation of the nonlinear phenomena, i.e. the super-harmonics due to the presence of the delamination damage in a composite plate, and to evaluate quantitively the influences of delamination existence on acoustic nonlinear properties of the composite plates. To achieve this, experiments of composite plates containing fabricated delamination damage generated by laser shock are conducted. Then a damage index is proposed based on total harmonic distortion (THD) to evaluate the effect of both the second and the third harmonics to the total nonlinear acoustic effects.

In this study, composed of 4 sections, the proposed damage index definition is described in Sect. 2. In Sect. 3 the configuration and results from experimental study is presented. Section 4 depicts the conclusion of this study and the future work in the next.

2 Damage Index Definition

In this study, the nonlinear Lamb waves are used for the delamination detection. For those nonlinear waves that are induced by delamination, not only the second harmonic, but also other higher order harmonics exist such as the third harmonic. However, in most studies only the effect of second harmonic is taken into account. Therefore, a damage index to evaluate the energy of multiple higher harmonics is necessary.

Total harmonic distortion (THD) is a common value used to measure the harmonic distortion present in a signal in audio system. It is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency:

$$THD = \frac{\sqrt{\sum_{i=2}^{N} A_i^2}}{A_1}, \tag{1}$$

where A_1 indicates the amplitude of the fundamental frequency, and A_i represents the amplitude of the ith order harmonic. Here, we set N = 3, indicating that only the energy of the second and third harmonic are calculated since the PZT sensor used in the experimental system is not sensitive enough to high frequency components. Then this THD becomes

$$THD = \frac{\sqrt{A_2^2 + A_3^2}}{A_1} \tag{2}$$

where A_2 and A_3 represent the amplitudes of the second and third harmonics respectively. Thus, the THD value in this study can be used to evaluate the total energy of the second and third harmonics with respect to the energy of the fundamental frequency. To evaluate quantitively the influence of the delamination damage in the specimens on the acoustic nonlinearity, a damage index (DI) is proposed based on the relative THD of damaged plates with respect to the healthy plate, which can be defined as

$$DI = \frac{THD_{damage} - THD_{healthy}}{THD_{healthy}}, \tag{3}$$

where THD_{damage} and $THD_{healthy}$ are the THD values of damaged plates and the undamaged plate respectively. This DI evaluates the effect of delamination existence on the acoustic nonlinearities of the system.

3 Experiments for Nonlinear Wave/Damage Interaction Characterization

3.1 Description of the SHM System

The study is conducted using a SHM system shown in Fig. 1(a) developed by the author's team. This system is composed of five components including the signal generator, amplifier, data acquisition system, multiplexer and the composite specimen equipped with two PZT disks. The specimen is suspended to the workbench, close to a stress-free boundary conditions to prevent the specimen from interacting with other supports. A schematic of the SHM experimental system is shown Fig. 1(b).

The specimens used here for testing are composite plates. These plates are made of carbon fiber reinforced polymer (CFRP) material consisting of 16 plies with the stacking sequence of $[0°/90°]_8$ and a dimension of 315 mm × 100 mm × 2.24 mm. Three damaged plates containing different sizes of delamination are used for damage detection, and a healthy plate is used for reference.

The pitch-catch method is used for the delamination damage detection. Each composite plate is equipped with two PZT disks (diameter 25 mm, thickness 0.5 mm; NCE51 material, provided by NOLIAC), as shown in Fig. 2. The PZT disks are permanently bonded to the surface of the composite plate. One PZT is used as transmitter and the other is used as signal receiver. The transmitter PZT1 is 50 mm away from the left edge and the receiver PZT2 is 45 mm from the right edge, ensuring a wave propagation distance of 220 mm.

When conducting experiments, input signals are launched by the signal generator and amplified by the amplifier. Then the multiplexer sends one signal to the transmitter and one signal to the data acquisition system. The transmitter converts the electrical signal to mechanical vibration to induce Lamb waves inside the plate. The waves propagate through the damage region inside the plate and arrive at PZT2. Then PZT2 transforms the elastic waves to electrical signals, and the signals are collected by the data acquisition system. The input signal is a five-cycle sine wave modulated by a sine window with the center frequency of 52 kHz. The measuring sampling frequency is 1 MHz, and the record length is 0.01 s to ensure the resolution of the received signals in frequency domain. The amplitude is 10 V from peak to zero.

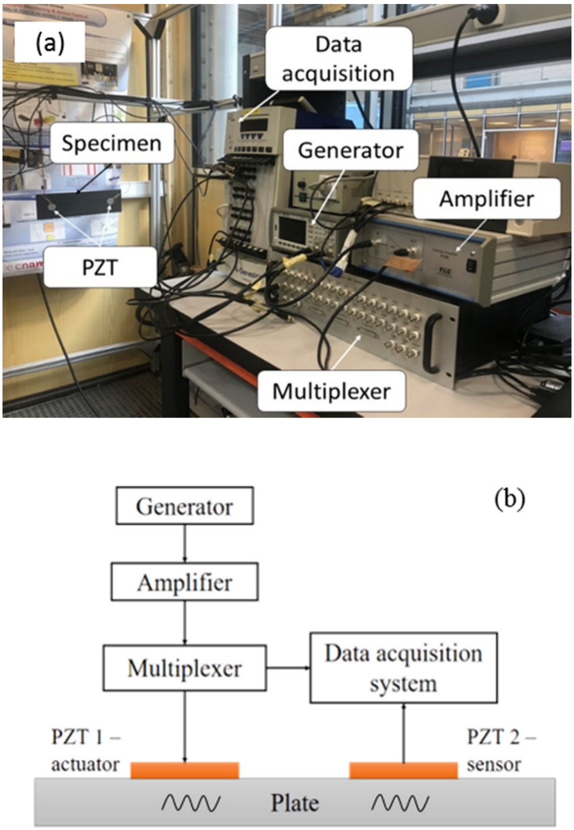

Fig. 1. (a) Experimental system; (b) schematic of the experimental system.

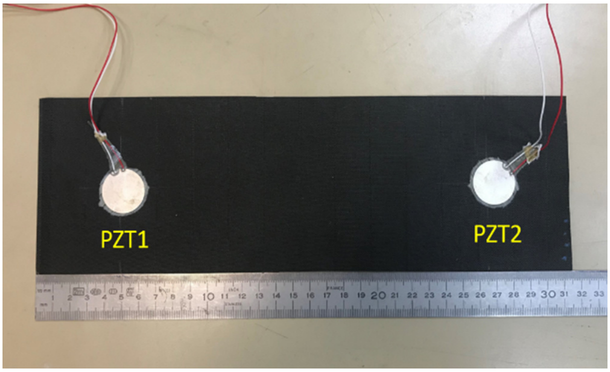

Fig. 2. Specimen: composite plate equipped with two PZTs

3.2 Damaged Specimens – Delamination Calibrated by Laser Shock

The damaged plate contains a circular delamination damage at the center. Damage was introduced into samples in a calibrated way using laser shock wave technique. The specimen was subjected to a symmetrical laser impact of two laser beams. This resulted in a nearly circular delamination of 7 mm diameter at midplane of the composite plate [12]. Figure 3 shows an example of the C-scan image of delamination damage calibrated by laser shock. In this example, the size and the in-depth position of this delamination is precisely determined by controlling the energy and time delay of the laser beams [13].

Four plates are considered here in this study, as shown in Fig. 4: the undamaged plate, the plate containing one laser impact that introduces the delamination-type damage at the diameter of 7 mm in the midplane of the plate, the plate containing two laser impact representing a delamination of approximately 14 mm created at midplane and the plate containing three laser impact representing a delamination of approximately 21 mm at midplane.

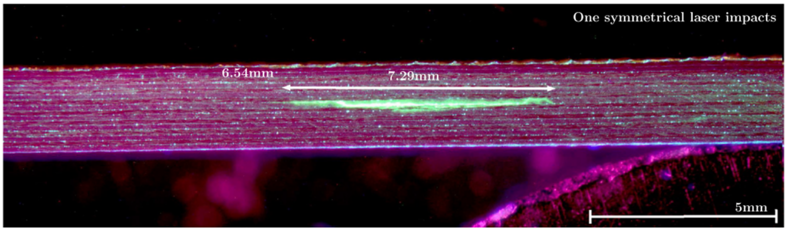

Fig. 3. C-scan of delamination damage calibrated by laser shock [13]

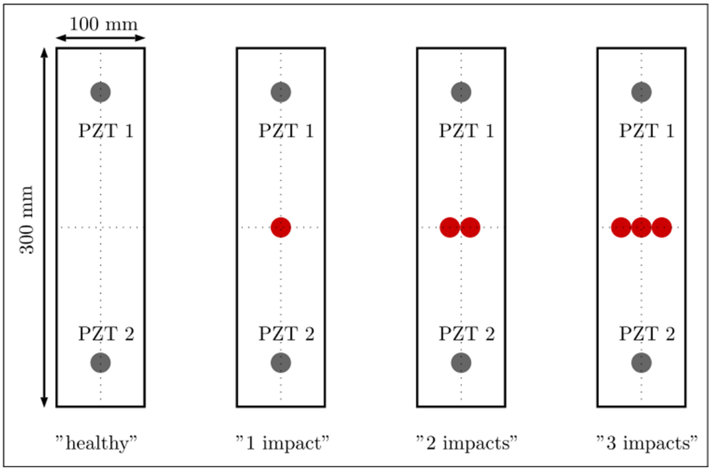

Fig. 4. Schematic representing the four plates, each equipped with 2 PZTs [12]

3.3 Experimental Results and Discussion

In this section, a five-cycle sine wave modulated by a sine window was used as the excitation signal. The results were shown in both time domain and frequency domain.

Figure 5 shows the comparison of the responses in frequency domain for the undamaged plate and the damaged plate containing two laser impacts under the excitation of the modulated wave excitation. From this figure, except for the peak at fundamental frequency, there are two perceptible peaks corresponding to the second and third harmonics (104 kHz and 156 kHz) respectively. In the insets of Fig. 5, the harmonics are given for comparison; the amplitudes of both the second and the third harmonics from the spectrum of the two-impact plate are larger than those from the undamaged plate. It can be concluded that the acoustic nonlinearities are enhanced by the presence of the delamination impacts. This can also be proved by showing the frequency spectrum of the residual signal between the two-impact damaged plate and the undamaged plate shown in Fig. 6. Note that the frequency amplitudes are normalized to the maximum value. Therefore, the super-harmonics, especially the second and third harmonics, provide a sensitive tool for the detection of laser impact delamination in composite plates.

Then the effects of delamination size and excitation amplitude on the acoustic nonlinearity are studied and presented in the following.

Figure 7 displays the variation of relative THD based DI against the number of delamination impacts under the excitation amplitude of 10 V and 50 V. From this figure, it can be observed that the DI increases monotonically with the number of delamination impacts regardless of the excitation amplitude. For the one-impact plate, the relative THD values of the two cases with different excitation amplitudes are close. However, for the two-impact and three-impact plates, the THD values of the case under excitation amplitude of 10 V is larger than the THD values under excitation at 50 V. This indicated that the proposed THD based DI is remarkably sensitive to the size of the delamination, but less sensitive to the excitation amplitudes.

Figure 8 presents the variation of relative THD based DI against the excitation amplitude on different specimens. The excitation amplitude varies from 10 V to 50 V at the step of 10 V. From this figure, it can be observed that the DI displays rather flat trends with some small variations with increasing excitation amplitudes. For the two-impact and the three-impact specimens, the two curves show a slightly decreasing trend of the Dis, while for the one-impact specimen, the DI curve is almost flat. This variation trend might be due to the nonlinearities of the system. In conclusion, compared to the influence of the damage size, the excitation amplitude has much less effects on the proposed DI.

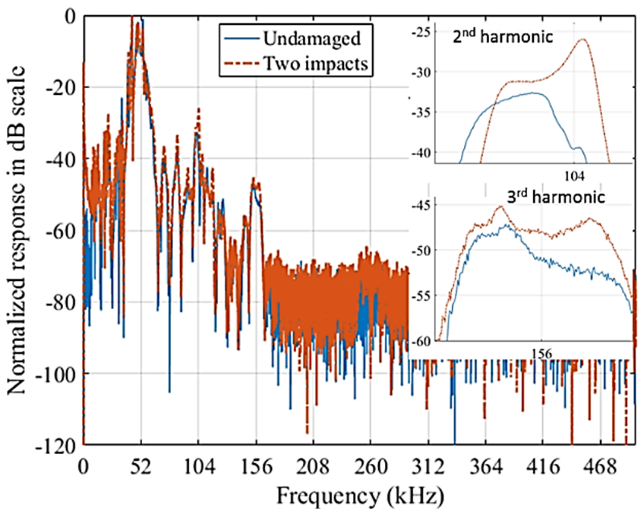

Fig. 5. Frequency domain responses of signals obtained from undamaged plate and damaged plate containing two impacts

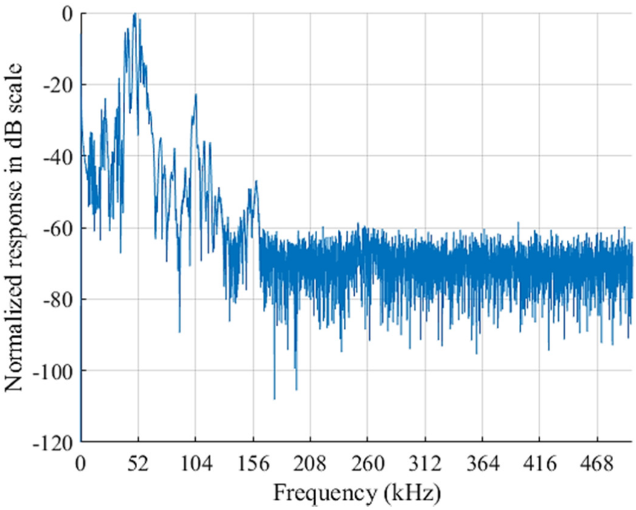

Fig. 6. Frequency spectrum of residual signal between the two-impact damaged plate and the undamaged plate subject to modulated wave excitation

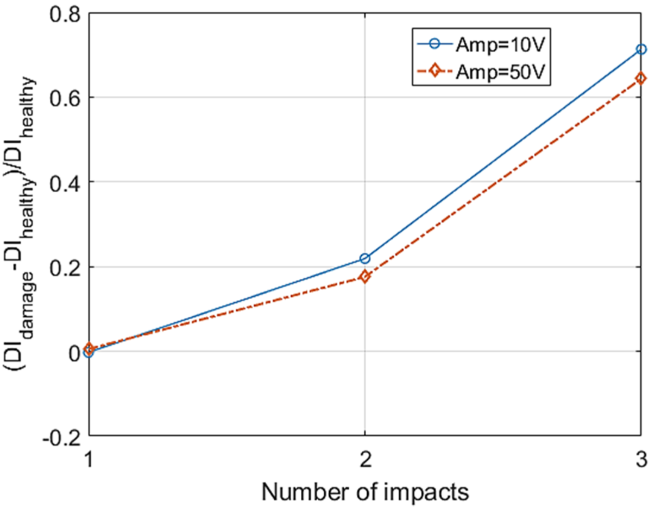

Fig. 7. Variation of DI based on relative THD against the number of delamination impacts for different excitation amplitudes

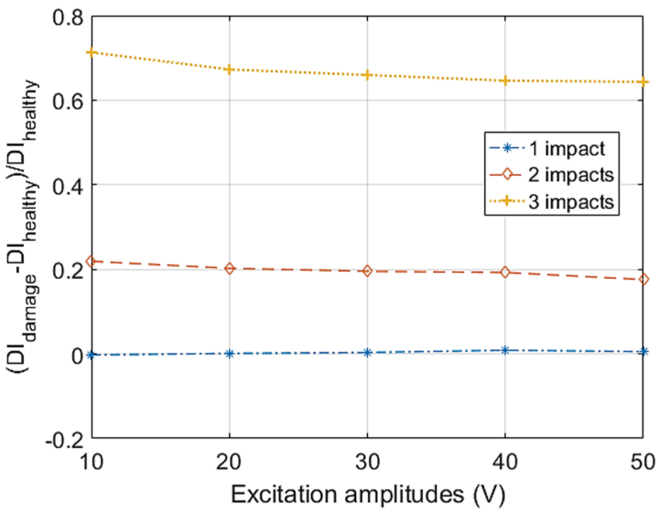

Fig. 8. Variation of DI based on relative THD against excitation amplitude on different specimens

4 Conclusion and Future Work

In this study, the acoustic nonlinearities due to the presence of damage was investigated, and a damage index based on the total harmonic distortion was proposed and validated experimentally.

The experiments were conducted under the excitation of a five-cycle sine wave modulated by a sine window at 52 kHz. From the experimental results, it can be concluded that the presence of delamination damage enhances the nonlinearities of the Lamb waves propagating in the composite plate. A new DI based on relative THD values is proposed and used for the evaluation of the acoustic nonlinearities. Results show that the proposed DI is remarkably sensitive to the size of the delamination, but less sensitive to the excitation amplitudes.

In future studies, the finite element simulations will be conducted and the effects of excitation amplitude and damage size on the severity of the nonlinearities are going to be investigated numerically. Different damage indices will be generated and evaluated as indicators of the severity of the damage. Next, the results of experiments and simulations will be applied to the SHM process.

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